

RESEARCH ARTICLE

The Correlation between Running Economy and Maximal Oxygen Uptake: Cross-Sectional and Longitudinal Relationships in Highly Trained Distance Runners

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Abstract

A positive relationship between running economy and maximal oxygen uptake ($\dot{V}O_{2max}$) has been postulated in trained athletes, but previous evidence is equivocal and could have been confounded by statistical artefacts. Whether this relationship is preserved in response to running training (changes in running economy and $\dot{V}O_{2max}$) has yet to be explored. This study examined the relationships of (i) running economy and $\dot{V}O_{2max}$ between runners, and (ii) the changes in running economy and $\dot{V}O_{2max}$ that occur within runners in response to habitual training. 168 trained distance runners (males, $n = 98$, $\dot{V}O_{2max}$ 73.0 ± 6.3 mL·kg⁻¹·min⁻¹; females, $n = 70$, $\dot{V}O_{2max}$ 65.2 ± 5.9 mL·kg⁻¹·min⁻¹) performed a discontinuous submaximal running test to determine running economy (kcal·km⁻¹). A continuous incremental treadmill running test to volitional exhaustion was used to determine $\dot{V}O_{2max}$ 54 participants (males, $n = 27$; females, $n = 27$) also completed at least one follow up assessment. Partial correlation analysis revealed small positive relationships between running economy and $\dot{V}O_{2max}$ (males $r = 0.26$, females $r = 0.25$; $P < 0.006$), in addition to moderate positive relationships between the changes in running economy and $\dot{V}O_{2max}$ in response to habitual training ($r = 0.35$; $P < 0.001$). In conclusion, the current investigation demonstrates that only a small to moderate relationship exists between running economy and $\dot{V}O_{2max}$ in highly trained distance runners. With >85% of the variance in these parameters unexplained by this relationship, these findings reaffirm that running economy and $\dot{V}O_{2max}$ are primarily determined independently.

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Introduction

Running economy (RE) and maximal oxygen uptake ($\dot{V}O_{2max}$) are two of the primary determinants of endurance running performance [1–4]. The combination of RE and $\dot{V}O_{2max}$ defined as the velocity at $\dot{V}O_{2max}$ ($v\dot{V}O_{2max}$), has been found to account for ~94% of the inter-individual

variance in running performance over 16.1 km [5]. Consequently, exceptional values of both RE and $\dot{V}O_{2\max}$ are considered requirements for success in elite endurance competitions, and endurance runners strive to improve both parameters through training in order to maximise performance. As the margin of success is extremely small in elite distance running, subtle enhancements in either parameter could result in substantial performance gains. Therefore, understanding the relationship of RE and $\dot{V}O_{2\max}$ both between and within individuals is necessary to understand and optimise performance.

Within cohorts of trained [6,7] and elite [8] distance runners, it has been suggested that a superior RE, quantified as the submaximal oxygen uptake, is associated with a lower $\dot{V}O_{2\max}$. These findings have been used to postulate that superior economy compensates for a lower $\dot{V}O_{2\max}$ in some individual to achieve a similar performance level [3,8,9]. However, these investigations have often been restricted to small sample sizes (<25 participants [3,6,8]), and the validity of their statistical techniques has been questioned due to the expression both variables relative to body mass (i.e. $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$); creating a common divisor that is known to produce spurious correlations [10]. Partial correlation analysis would provide an appropriate method to account for the influence of body mass on both variables whilst avoiding statistical artefacts, however this method has yet to be used to examine the relationship between RE and $\dot{V}O_{2\max}$. Furthermore, studies have solely employed oxygen cost (O_C) as a measure of RE, rather than the more valid and comprehensive measurement of energy cost (E_C ; [11]). Thus, whether a genuine association exists between RE and $\dot{V}O_{2\max}$ remains unclear from the limited cross-sectional observations to date.

Moreover, the concurrent alterations in RE and $\dot{V}O_{2\max}$ that occur within athletes over time with training might further reveal if there is an inherent association between these variables, whilst also informing the optimisation of both variables and thus performance. Previous investigations in well trained athletes have noted enhancements in cycling efficiency following short-term, intensive endurance training, but with no change in $\dot{V}O_{2\max}$ evident [9,12,13]. In contrast, a recent investigation reported an association between individual changes in cycling efficiency and $\dot{V}O_{2\max}$ in response to endurance training and across a competitive season; despite no change in mean group $\dot{V}O_{2\max}$ [14]. These preliminary findings highlight the significance of this relationship for elite endurance athletes, as enhancements in either RE or $\dot{V}O_{2\max}$ might only be achievable at the expense of the other variable. However, this previous investigation was limited to measurements of gross efficiency, with no data presented on movement economy. Moreover, analysis of this longitudinal relationship was restricted to observations within small cohorts of athletes, and with responses to run training yet to be explored.

The primary aim of the current investigation was to explore the cross-sectional relationship between $\dot{V}O_{2\max}$ and RE, quantified as E_C (O_C data are also presented for comparative purposes), within a large cohort of highly trained distance runners. The secondary aim was to examine the longitudinal relationship between the changes in $\dot{V}O_{2\max}$ and RE occurring within athletes in response to endurance training.

Materials and Methods

Overview

The cross-sectional investigation involved retrospective analysis of data from 168 healthy endurance trained athletes with competitive distances ranging from 800m to the marathon (males, $n = 98$; females, $n = 70$; Table 1), who undertook testing and monitoring as part of their sport science support from the English Institute of Sport. The following tests were performed after written informed consent was obtained as a part of sports science support provision, with procedures approved by the Internal Review Board of English Institute of Sport. Of the

Table 1. Physiological and anthropometrical characteristics of athletes within the cross sectional and longitudinal investigations.

	Cross sectional		Longitudinal sub-group	
	Females (n = 70)	Males (n = 98)	Females (n = 27)	Males (n = 27)
Age (yrs)	23±4	23±6	23±5	21±3
Body mass (kg)	55.2±4.7	67.1±7.1	55.4±4.3	66.6±6.0
Stature (cm)	169±5	179±7	168±4	179±6
$\dot{V}O_{2\max}$ (mL·kg ⁻¹ ·min ⁻¹)	65.2±5.9	73.0±6.3	64.5±4.9	73.6±5.9
vLTP (km·h ⁻¹)	15.5±1.2	17.2±1.3	15.7±1.2	17.6±1.1
Running economy (kcal·kg ⁻¹ ·km ⁻¹)	1.15±0.09	1.14±0.09	1.13±0.06	1.13±0.07

$\dot{V}O_{2\max}$, maximal oxygen uptake; vLTP, velocity at lactate turnpoint.

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participants assessed, 97 (males, n = 57; females, n = 40) were classed as middle distance runners, defined by a primary competitive distance ≤ 3000 m [15], with 71 classed as long distance runners (males, n = 41; females, n = 30). During the season following their final visit, athlete's best performance times in their primary competitive distance were $89.1 \pm 6.1\%$ and $91.2 \pm 4.4\%$ of the current British record for males and females, respectively. Data were collected from two laboratories, with all tests conducted as part of athlete support services between November 2004 and April 2013. Participants provided informed consent prior to physiological assessments, in addition to an athlete agreement providing permission for the use of their data in anonymous retrospective analysis. During each visit to the laboratory, participants completed first submaximal and then maximal running assessments (detailed below). Participants wore appropriate clothing (shorts and a vest or t-shirt) and racing shoes, and laboratory conditions were similar throughout all running assessments (temperature $20.6 \pm 1.9^\circ\text{C}$, relative humidity $45.9 \pm 9.8\%$). As differences in RE and $\dot{V}O_{2\max}$ have been noted between sexes [16–18], males and females were analysed separately for cross sectional analyses.

The longitudinal aspect of the study was based on 54 participants (males, n = 27; females, n = 27) from amongst the larger cohort of 168 runners, that had completed at least one follow up assessment, with a median trial separation of 203 days (range: 37–2567 days) in order to assess within-athlete changes in both RE and $\dot{V}O_{2\max}$ over time. The number of repeat assessments in the longitudinal analysis varied between participants, with a median of 3 visits per athlete (range: 2–10 visits), summing to 182 assessments in total. No evidence is currently available regarding sex differences in the concurrent alterations in RE and $\dot{V}O_{2\max}$ in response to habitual endurance training, thus data for males and females were combined for longitudinal analysis.

Protocol

Submaximal running assessments. Following a warm-up (~10 min at $10\text{--}12\text{ km}\cdot\text{h}^{-1}$), participants completed a discontinuous submaximal incremental test consisting of six to nine stages of 3 minutes continuous running, with increments of $1\text{ km}\cdot\text{h}^{-1}$ on a motorised treadmill of known belt speeds (HP cosmos Saturn, Traunstein, Germany) interspersed by 30 s rest periods for blood sampling. As the speeds assessed were typically between $10.5\text{ km}\cdot\text{h}^{-1}$ and $18\text{ km}\cdot\text{h}^{-1}$, treadmill gradient was maintained at 1% throughout submaximal assessments in order to reflect the energetic cost of outdoor running [19]. This protocol has been shown to reliable measures of running economy when quantified as both E_C and O_C (typical error ~3%; [20]). Moreover, the controlled laboratory environment enabled assessments of E_C whilst avoiding the confounding influence of air resistance that is evident during outdoor running as speed

increases [21]. Recent performance times of participants were used to determine an appropriate starting speed to provide ~4 speeds prior to lactate turnpoint (LTP). Increments were continued until blood lactate concentration had risen exponentially, typically defined as an increase in blood lactate of $\sim 2 \text{ mmol}\cdot\text{L}^{-1}$ from the previous stage. HR (s610i, Polar, Finland) and pulmonary gas exchange (detailed below) were monitored throughout the test.

Maximal running assessments. $\dot{V}O_{2\max}$ was determined by a continuous incremental treadmill running ramp test to volitional exhaustion. After a warm-up, participants initially ran at a speed $2 \text{ km}\cdot\text{h}^{-1}$ below the final speed of the submaximal test and at a 1% gradient. Each minute, the incline was increased by 1% until volitional exhaustion. The test duration was typically 6–8 minutes.

Measurements

Anthropometry. Prior to exercise on laboratory visits, body mass was measured using digital scales (Seca 700, Seca, Hamburg, Germany) to the nearest 0.1 kg. Stature was recorded to the nearest 1 cm using a stadiometer (Harpenden Stadiometer, Holtain Limited, UK).

Pulmonary gas exchange. Breath-by-breath gas exchange data was quantified via an automated open circuit metabolic cart (Oxycon Pro, Carefusion, San Diego, USA). Participants breathed through a low dead-space mask, with air sampled at $60 \text{ mL}\cdot\text{min}^{-1}$. Prior to each test, two point calibrations of both gas sensors were completed, using a known gas mixture (16% O_2 , 5% CO_2) and ambient air. Ventilatory volume was calibrated using a 3 L ($\pm 0.4\%$) syringe. This system has previously been shown to be a valid apparatus for the determination of oxygen consumption ($\dot{V}O_2$) and carbon dioxide production ($\dot{V}CO_2$) at both low and maximal exercise intensities [22]. As previous data from our laboratory has demonstrated a steady state $\dot{V}O_2$, and $\dot{V}CO_2$ is achieved within the first 2 minutes of each stage for highly trained endurance runners [20], mean values from breathe-by-breathe measures over the final 60 seconds of each stage were used to quantify $\dot{V}O_2$, carbon dioxide production $\dot{V}CO_2$, and RER.

Blood lactate. A $20\mu\text{L}$ capillary blood sample was taken from the earlobe for analysis of blood lactate ($[La]_b$) (Biosen C-line, EKF diagnostics, Germany). The LTP was identified via the modified Dmax method [23]. LTP was quantified as the point on the third order polynomial curve fitted to the speed-lactate relationship that generated the greatest perpendicular distance to the straight line formed between the stage proceeding an increase in $[La]_b$ greater than $0.4 \text{ mmol}\cdot\text{L}^{-1}$ (lactate threshold) and the final stage. The four stages prior to LTP were identified for each participant, with an average of these four stages used to quantify O_C and E_C .

Calculation of running economy. $\dot{V}O_2$ and $\dot{V}CO_2$ during the final minute of each submaximal stage were used to calculate E_C . Updated nonprotein respiratory quotient equations [24] were used to estimate substrate utilisation ($\text{g}\cdot\text{min}^{-1}$) during the monitored period. The energy derived from each substrate was then calculated by multiplying fat and carbohydrate usage by 9.75 kcal and 4.07 kcal, respectively, reflecting the mean energy content of the metabolised substrates during moderate to high intensity exercise [25]. E_C was quantified as the sum of these values, expressed in $\text{kcal}\cdot\text{km}^{-1}$. $\dot{V}O_2$ during the final minute of each submaximal stage was used to determine oxygen cost (O_C) in $\text{mL}\cdot\text{km}^{-1}$ to enable comparisons to previous investigations.

Statistical analyses. Data are presented as mean \pm SD for all dependant variables. Data analysis was conducted using SPSS for windows (v21; IBM Corporation, Armonk, NY). When an individual visited the laboratory for repeated assessments, an average of the assessments was calculated and used for the cross sectional analysis. Pearsons product-moment coefficients were calculated to assess the relationship between body mass and E_C , O_C and $\dot{V}O_{2\max}$. As body mass was strongly related to both RE measures (E_C , O_C) and $\dot{V}O_{2\max}$, partial correlations

controlling for body mass, and associated 95% confidence intervals (CI), were used to assess the relationship between absolute $\dot{V}O_{2\max}$ and both E_C and O_C . This method removes the influence of body mass on both RE and $\dot{V}O_{2\max}$ whilst avoiding spurious correlations created by correlating two variables with a common divisor [26]. For graphical display of these relationships, values of E_C and $\dot{V}O_{2\max}$ adjusted for body mass for each individual were calculated based on individual residuals. This involved summing the individual's residual, in comparison to the cohort relationship with body mass (e.g. EC vs body mass), with the group mean for that variable [27]. For the longitudinal analysis, in order to assess any relationships between the changes over time in absolute $\dot{V}O_{2\max}$ and the changes in both E_C and O_C over repeat visits, partial correlation coefficients were calculated using ANCOVA [28]; providing a comprehensive model that accounts variations in both body mass and the number of visits per athlete. Cohen's d effect size descriptors (trivial 0.0–0.1, small 0.1–0.3, moderate 0.3–0.5, large 0.5–0.7, very large 0.7–0.9, nearly perfect 0.9–1, perfect 1) were used to infer correlation magnitude [29]. Significance was accepted at $P \leq 0.05$.

Results

Participant Characteristics

Participant characteristics are shown in Table 1. The well trained status of the participants was emphasised by the high $\dot{V}O_{2\max}$ and vLTP values for both males and females.

Cross-sectional analysis

Partial correlation analysis controlling for body mass, revealed small positive relationships between E_C and $\dot{V}O_{2\max}$ (males $r = 0.26$, CI 0.07–0.44, $P = 0.009$; females $r = 0.25$, CI 0.02–0.46, $P = 0.036$; Fig 1), and a moderate positive relationship between O_C and $\dot{V}O_{2\max}$ (males $r = 0.33$, CI 0.14–0.50, $P = 0.001$; females $r = 0.33$, CI 0.10–0.52, $P = 0.006$).

Longitudinal analysis

Partial correlation analysis from ANCOVA revealed moderate positive relationships between the changes in E_C and $\dot{V}O_{2\max}$ over time ($r = 0.35$; CI 0.19–0.49, $P < 0.001$; Fig 2), and changes in O_C and $\dot{V}O_{2\max}$ over time ($r = 0.44$; CI 0.29–0.57, $P < 0.001$).

Discussion

The present investigation explored the cross-sectional and longitudinal relationships between RE and $\dot{V}O_{2\max}$ in a large cohort of highly trained distance runners. The major contribution of this study to the field is that only a small to moderate association exists between RE and $\dot{V}O_{2\max}$ ($R^2 \sim 12\%$) when body mass is appropriately accounted for. With >85% of the variance in these parameters unexplained by this relationship, these findings reaffirm that RE and $\dot{V}O_{2\max}$ are primarily determined independently.

Cross-sectional analysis revealed a small positive between-participant relationships between $\dot{V}O_{2\max}$ and the metabolic cost of running, when quantified as both E_C ($r \sim 0.25$) and O_C ($r \sim 0.33$). These results support the findings of Pate et al. [7], who reported a similar relationship ($r = 0.29$) between submaximal $\dot{V}O_2$ and $\dot{V}O_{2\max}$ in a similarly large cohort of habitual distance runners. Conversely, a stronger, moderate positive relationship has been reported between submaximal $\dot{V}O_2$ and $\dot{V}O_{2\max}$ in smaller cohorts of elite distance runners ($r = 0.59$; [8]) and physically active individuals ($r = 0.48$; [30]). However, all aforementioned investigations are confounded by statistical artefacts that arise when correlating two variables with common divisors [10,26], and thus should be regarded with caution. Within the current study, spurious

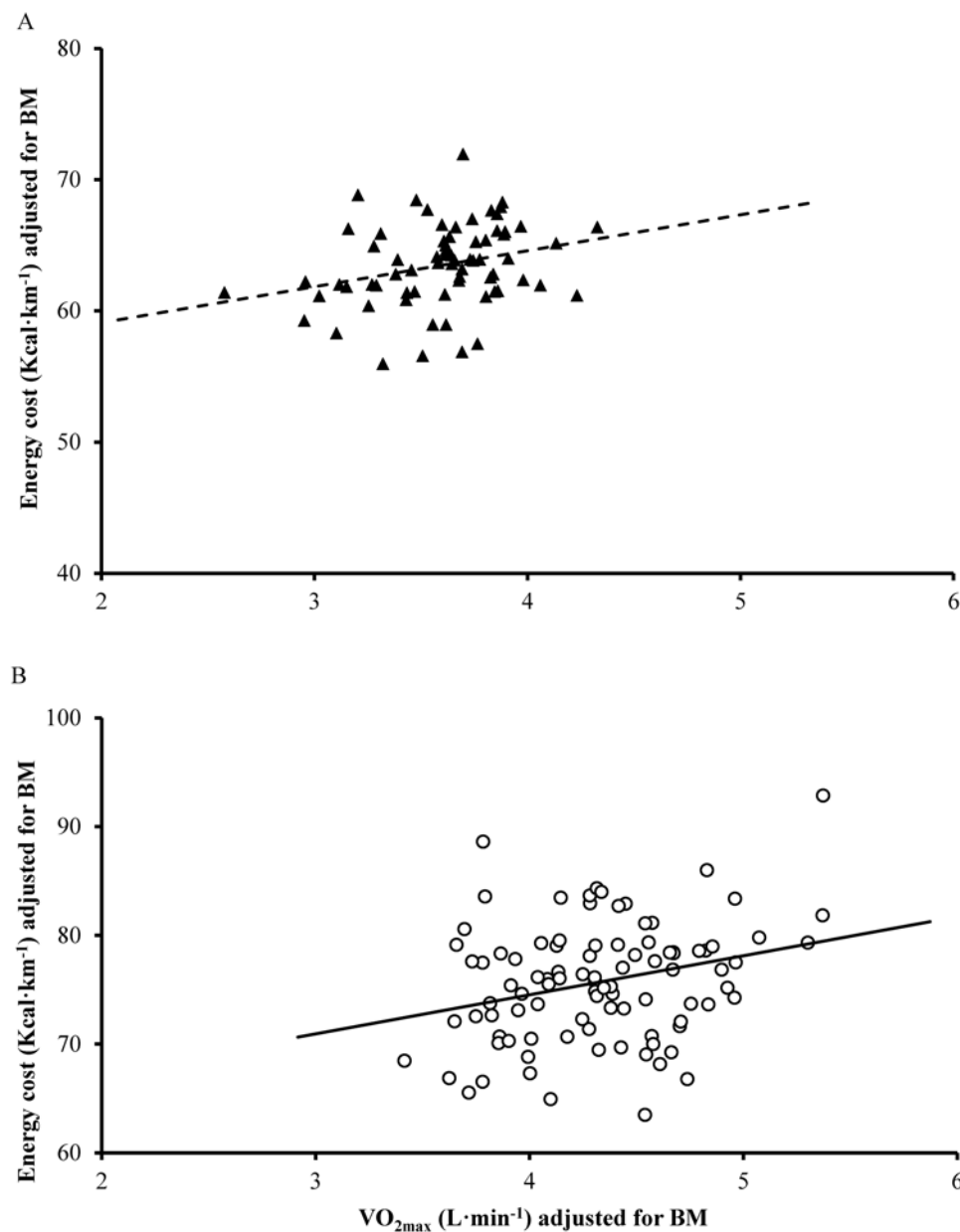


Fig 1. Scatter plot of energy cost (Kcal·km⁻¹) adjusted for body mass (BM) vs $\dot{V}O_{2\max}$ (L·min⁻¹) adjusted for BM for both females (A; $n = 70$; $r = 0.25$; $P = 0.036$) and males (B; $n = 98$; $r = 0.26$; $P = 0.009$) within the cross-sectional analysis.

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correlations between RE and $\dot{V}O_{2\max}$ were avoided by removing the influence of body mass with partial correlations, which enabled the true relationship between these variables to be examined. As a lower metabolic cost is reflective of a more economical runner, our findings confirm the existence of a small inverse association between RE and $\dot{V}O_{2\max}$ in endurance runners.

The longitudinal analysis of the relationship between the changes in RE and the changes in $\dot{V}O_{2\max}$ within participants in response to training has not previously been documented. Supporting the findings from our cross sectional analysis, a moderate positive relationship ($r = 0.35$) was observed between the changes in E_C and $\dot{V}O_{2\max}$ over repeated assessments.

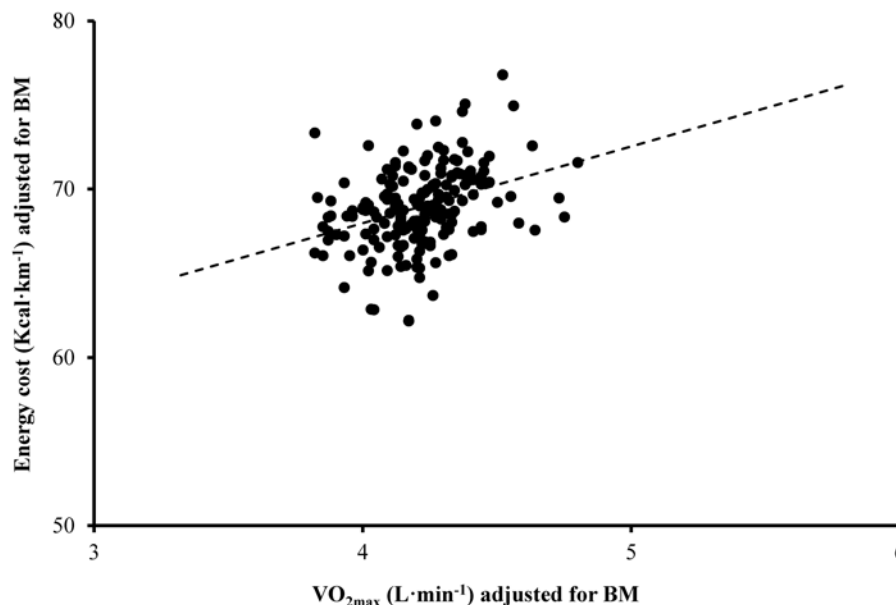


Fig 2. Scatter plot of the changes over time in energy cost ($\text{Kcal} \cdot \text{km}^{-1}$) adjusted for body mass (BM) vs the changes over time in $\dot{V}O_{2\max}$ ($\text{L} \cdot \text{min}^{-1}$) adjusted for BM ($r = 0.35$; $P < 0.001$) within the longitudinal analysis.

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Moreover, these findings support recent observations from competitive road cyclists that highlighted a similar moderate relationship ($r = 0.44$) between changes in gross efficiency and $\dot{V}O_{2\max}$ across a training season [14].

It has been postulated that variations in lipid oxidation rates between individuals might, in part, explain the relationship between O_C and $\dot{V}O_{2\max}$ that some previous studies have documented; with a higher $\dot{V}O_{2\max}$ facilitating greater lipid oxidation and consequently a greater O_C during sub-maximal exercise [7]. Whilst O_C may be sensitive to lipid oxidation, the calculation of E_C includes the RER and thus is insensitive to differences in substrate metabolism. The influence of substrate metabolism could conceivably explain the marginally stronger relationship observed between O_C and $\dot{V}O_{2\max}$, than E_C and $\dot{V}O_{2\max}$, in both the cross sectional ($r \sim 0.33$ vs $r \sim 0.25$) and longitudinal observations ($r = 0.44$ vs $r = 0.35$). More importantly, a positive relationship was documented between E_C and $\dot{V}O_{2\max}$ that is clearly independent of variations in lipid metabolism.

The mechanisms that underpin the small relationship between E_C and $\dot{V}O_{2\max}$ remain unclear. It has been argued that for athletes of a similar, high performance level, there would be an inevitable relationship between E_C and $\dot{V}O_{2\max}$ in order to produce a similar velocity at $\dot{V}O_{2\max}$ [31]. However, we have found no evidence for this possibility, despite all the participants in this study being highly trained and high performing runners, perhaps in part because of the variable performance ability of the athletes. It is also possible that less economical runners recruit a larger muscle mass (braking, oscillation etc.) and it is conceivable that this could contribute to a higher $\dot{V}O_{2\max}$. However there is considerable evidence that $\dot{V}O_{2\max}$ during whole body exercise such as running is largely dependent on oxygen delivery rather than utilisation [32], which might question this explanation. Thus, further investigation would be required to identify the factors driving the interdependence of E_C and $\dot{V}O_{2\max}$.

Though reaching statistical significance, the association between RE and $\dot{V}O_{2\max}$ was small. The current study found only $\sim 7\%$ (between-participant cross sectional data) and 12%

(within-participant longitudinal data) of the variance in RE was explained by $\dot{V}O_{2\max}$. This small association likely reflects the distinct nature of these variables and their physiological determinants. $\dot{V}O_{2\max}$ is known to be determined by factors such as cardiac output [33], total haemoglobin mass [34], and mitochondrial capacity [1]. Conversely, RE is thought to be closely associated to multiple biomechanical and anthropometrical factors, including effective storage and re-utilisation of elastic energy [35,36], vertical oscillation [37] and ground contact time [38]. As there are few common determinants of both RE and $\dot{V}O_{2\max}$, adaptations that lead to enhancements in one of these variables are unlikely to directly influence in the opposing variable.

In conclusion, the current investigation demonstrates that only a small to moderate relationship exists between running economy and $\dot{V}O_{2\max}$ in highly trained distance runners. With >85% of the variance in these parameters unexplained by this relationship, these findings reaffirm that running economy and $\dot{V}O_{2\max}$ are primarily determined independently.

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Author Contributions

Conceived and designed the experiments: AJS JPF SAI. Performed the experiments: AJS JPF SAI. Analyzed the data: AJS JPF SAI GA. Contributed reagents/materials/analysis tools: AJS JPF SAI GA. Wrote the paper: AJS JPF SAI GA.

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